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Signal-to-Solar Clutter Calculations of AK-47 Muzzle Flash at Various Spectral Bandpass Near the Potassium D1/D2 Doublet

by Karl K. Klett, Jr.

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Signal-to-solar clutter calculations of AK-47 muzzle flash at various spectral bandpasses near the Potassium D1/D2 doublet

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ABSTRACT

An analysis was performed, using MODTRAN, to determine the best filters to use for detecting the muzzle flash of an AK-47 in daylight conditions in the desert. Filters with bandwidths of 0.05, 0.1, 0.5, 1.0, 3.0, and 5.0 nanometers (nm) were analyzed to understand how the optical bandwidth affects the signal-to-solar clutter ratio. These filters were evaluated near the potassium D1 and D2 doublet emission lines that occur at 769.89 and 766.49 nm respectively that are observed where projectile propellants are used. The maximum spectral radiance, from the AK-47 muzzle flash, is 1.88 x 10^{-2} W/cm^2 str micron, and is approximately equal to the daytime atmospheric spectral radiance. The increased emission, due to the potassium doublet lines, and decreased atmospheric transmission, due to oxygen absorption, combine to create a condition where the signal-to-solar clutter ratio is greater than 1. The 3 nm filter, has a signal-to-solar clutter ratio of 2.09 when centered at 765.37 nm and provides the best combination of both cost and signal sensitivity.

Keywords: small arms muzzle flash, AK-47, threat detection, potassium doublet, atmospheric radiance.

1.0 INTRODUCTION

The Survivability/Lethality Analysis Directorate (SLAD) and the Sensors and Electron Devices Directorate (SEDD) of the Army Research Laboratory (ARL) are developing spectral techniques to detect the potassium D1 and D2 doublet emission lines in daylight conditions, occurring at 769.89 and 766.49 nm respectively, in the muzzle flash from various weapon systems that may be used against U.S. forces. It is hoped that these visible spectral techniques will improve upon acoustic based detection systems that are inexpensive but are limited by the speed of sound, providing their threat information after the threat weapon has caused its damage[1].

The mid-wave infrared (MWIR) has been explored for the detection of small arms fires since the 1960s[2-3]. An early Advanced Concept Technology Demonstration (ACTD) of the MWIR technology called VIPER was performed in 1996, and showed that small arms muzzle flashes (50 caliber and smaller) could be detected at and beyond the maximum effective range of the weapon[4-5]. These MWIR sensor systems provide good signal detection because of the high temperature associated with the muzzle flash of small arms weapons. However, MWIR systems are costly and impose added expenses due to the cooling requirements of sensors and increased life-cycle costs caused by the limited operational lifetime of such systems.

Recent efforts are underway at ARL[6-7] to develop a sensor that uses a silicon based focal plane array and visible optics to develop a low cost small arms threat detection system. Such a system uses the narrow potassium

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emission line doublet that is present in small arms secondary muzzle flash. Potassium salts are added to the projectile propellant to reduce the secondary muzzle flash, which temporarily blinds the shooter's vision[8-9]. The irony of the use of potassium salts as a muzzle flash suppressant in projectile propellant is that the potassium salts, which reduce the muzzle flash, also emit two strong emission lines that can be used to detect the suppressed muzzle flash.

The detection of the narrow potassium emission lines from the muzzle flash of small arms, during daylight conditions, is a difficult problem, because the radiance of the line emission doublet is masked by solar radiation scattered from the atmosphere and solar radiation reflected from the ground. It is the purpose of this analysis, using an atmospheric radiometry program developed by the Air Force called MODTRAN, to identify filters that might be used to detect potassium line emission features in the muzzle flash of small arms fire.

2.0 MODTRAN modeling of the atmosphere

Scattered atmosphere and ground reflected spectral radiances were calculated using PcModWin 4.0 v3r1, version 1.4.0, which is a commercial graphical environment used to set up, run, and manipulate model calculations made by MODTRAN atmospheric code. PcModWin is made by ONTAR corporation. MODTRAN was developed by the Air Force to calculate the spectral transmittance and radiance for arbitrary atmospheric paths from the microwave through visible bands. PcModWin is used here to calculate the spectral radiance from the atmosphere and the reflected solar radiation that scatters in the atmosphere[12].

The following assumptions were input into MODTRAN:

- Radiances are calculated with multiple scattering.
- Albedo (0.4) is based on a desert environment.
- Aerosol model is a rural setting with 5 km visibility.
- Observer height is 30 m looking down on a slant angle at a target at 0 elevation.
- Observer to target distance is 300 m.
- Wavelengths evaluated: 700 nm - 835 nm.
- Model resolution: 1 cm^{-1}.
- Sun zenith angle: 30 degrees.
- Azimuth angle at observer to the sun: 0 degrees.

Additional assumptions, not related to MODTRAN are:

- The focal plane array quantum efficiency near 766 nm is 100%.
- Evaluated filters for this analysis have full width at half the maximum value (FWHM) bandpasses of 0.05 nm, 0.1 nm, 0.5 nm, 1 nm, 3 nm, and 5 nm.
- For the above bandpasses, assume 0% out-of-band and 100% in-band transmission.

Figure 1, on the next page, plots various atmospheric and reflected spectral radiances from 700 nm to 835 nm. The total radiance (blue, top plot in figure 1) is the sum of the path thermal radiance, multiple scattering, surface emission, and ground reflected radiance. The thermal radiance is the radiance emitted by the atmosphere in the path of transmission, and since multiple scattering is selected as an option, this includes the boundary emission at the air ground boundary, and the thermal radiation scattered into the atmospheric path by the atmosphere itself or the ground. The surface emission is the radiance emitted from the surface at a specified temperature and emissivity (albedo). The ground reflected radiance (magenta-middle plot in figure 1) is the solar radiance reflected into the transmission path by the ground. Finally, the scattered direct solar radiation (green-bottom plot in figure 1) is the solar radiation scattered into the transmission path, within the atmosphere, before reaching the ground[12-13].

Figure 1 also shows that atmospheric absorption between 0.76 and 0.77 microns, caused by oxygen, coincides with the potassium emission doublet lines. This spectral absorption feature, referred to as the oxygen "A" band, centered near 761.9 nm is a forbidden transition, and although a weak transition, shows up on spectra as a strong absorption feature due to the large amounts of oxygen in the atmosphere[14]. As mentioned above, the potassium emission doublet lines occur between 0.76 and 0.79 microns. It is this combination of conditions, where higher muzzle flash radiance, due to the potassium emission lines, and lower atmospheric radiance caused by atmospheric absorption, coincide to produce conditions that might be favorable for daylight small arms muzzle flash detection.

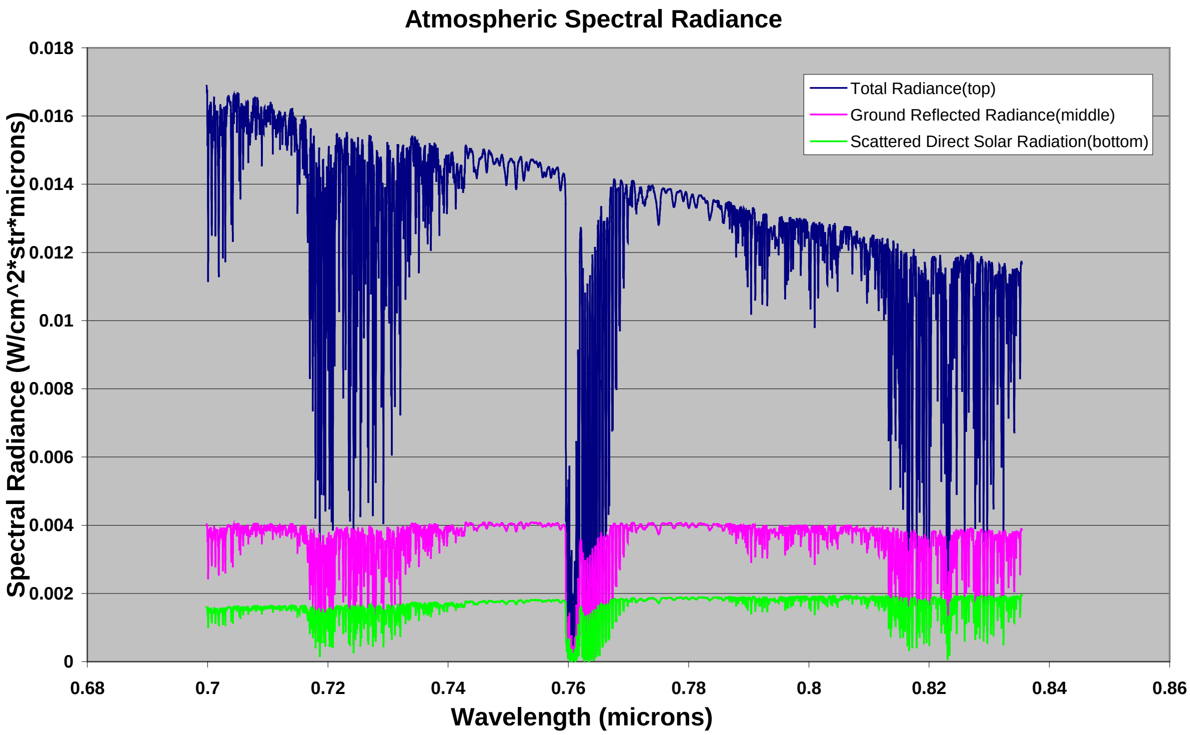

Figure 1. MODTRAN model atmosphere used in the AK-47 Muzzle Flash Analysis, showing Oxygen "A" absorption at 0.761 microns

3.0 A comparison of AK-47 muzzle flash spectra with atmospheric spectra

High speed and high resolution spectra were obtained of the muzzle flashes of AK-47 rounds by SLAD in May, 2007. These tests used a high speed radiometer, a high speed filtered imager, and a high speed/high resolution near-infrared (NIR) spectrometer. The average radiant intensity of the AK-47 muzzle flash is 50 microwatts/steradian, and the average temporal FWHM of the muzzle flash duration is 0.5 milliseconds [15-16].

Figure 2, plots the spectral radiance of a typical AK-47 muzzle flash and the atmospheric radiance so that the spectral features and relative intensities can be compared. The muzzle flash spectra, chosen in figures 2 and used for the analysis, is representative of the average from the multiple firings measured by SLAD.

Since MODTRAN's output is in units of spectral radiance (W/cm^2 str micron) and the muzzle flash's measurements were in units of radiant intensity (W/str nm), conversions were necessary. It was decided to convert radiant intensity to spectral radiance, and this was done in the standard way[17]. Radiant intensity was divided by the area of the measured muzzle flash (4-inch diameter muzzle flash) and the muzzle flash

measurements were multiplied by 500 since the time signature of the AK-47 muzzle flash lasted 0.5 milliseconds FWHM and the spectra integration time was 1 microsecond.

Figure 2 shows that the measured potassium D2 doublet emission line (766.49 nm) overlaps with several atmospheric absorption features. These absorption features, their location with respect to the potassium doublet emission lines, and the larger ratios of the muzzle flash spectrum to the atmosphere's spectrum, seem to indicate that a careful selection of filters could provide the minimum three to one signal-to-noise ratio that is generally accepted as sufficient for signal detection using silicon based sensors[18].

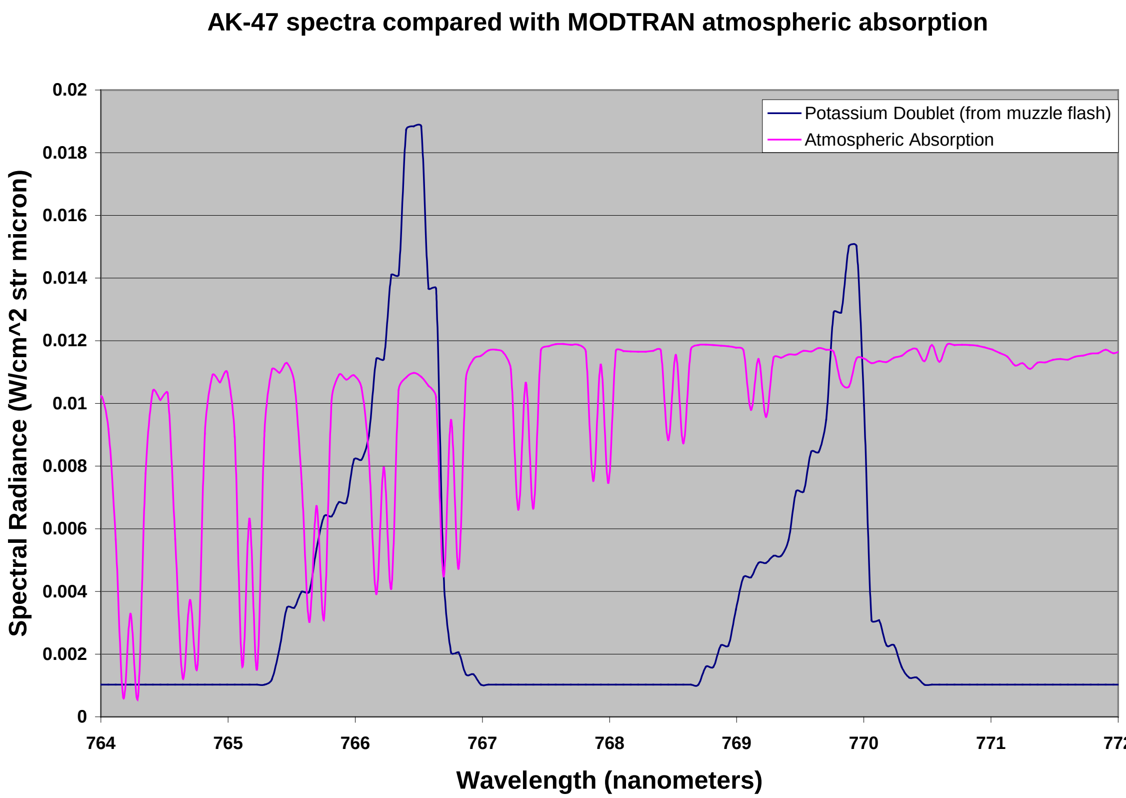

Figure 2. Atmosphere and AK-47 muzzle flash spectral radiance.

4.0 Calculating the signal-to-solar clutter ratio

The calculations, to be described, are similar to signal-to-noise calculations, where the signal is the AK-47 muzzle flash radiance and the noise is the solar radiance transmitted through the atmosphere to the sensor. The atmosphere spectral radiance was calculated using MODTRAN, as described above, and transported to an Excel spread sheet. The AK-47 radiant intensity values, provided by SLAD, were entered manually into an Excel spreadsheet at 0.1 nm resolution. MODTRAN's Resolution is 1 cm^{-1}, which corresponds to a 0.049 nm resolution at 700 nm and 0.064 nm resolution at 800 nm.

Calculations were made from 760 to 775 nm at the 1 cm^{-1} resolution of MODTRAN. This interval was chosen because it contained the potassium doublet lines that are the source of the muzzle flash signal. Filter widths (FWHM) of 0.05, 0.1, 0.5, 1, 3, and 5 nm were evaluated. The smallest filter width of 0.05 nm was chosen based on the minimum resolution of MODTRAN. The signal-to-solar clutter ratio was integrated for each filter, from the lower FWHM transmission wavelength of the filter to the upper FWHM transmission wavelength. This

calculation was repeated, increasing the starting wavelength of the integration at 1 cm^{-1} increments for the full 760-775 nm wavelength range of the analysis. The result of these sets of integrations, from 760 to 775 nm, were two numbers; the signal-to-solar clutter ratio at each 1 cm^{-1} increment, and the center wavelength where the integration was made. From these measurements, repeated for each filter, the center wavelength was determined where the signal-to-solar clutter ratio was a maximum. These maximum signal-to-solar clutter values were then compared to select the best filter, of the six analyzed, that would detect a small arms muzzle flash.

5.0 Analysis of the six filter integrations

Signal-to-solar clutter ratios were calculated for each of the six filters as they were moved at 1 cm^{-1} increments along the 760 to 775 nm wavelength interval . For each filter, the maximum signal-to-solar clutter ratio was noted and compared with the center wavelength of the filter where the maximum occurred. These maximum ratios were then compared for each filter width, making selection of the optimum filter possible.

5.1 Signal-to-solar clutter calculations

Figures 3-8 below, graph the signal-to-solar clutter ratios for the 0.05, 0.5, 0.1, 1.0, 3.0, and 5.0 nm filter widths. These figures provide a visual representation of how the signal-to-solar clutter ratio changes with center wavelength and the filter's FWHM width.

The effects of atmospheric absorption are most clearly seen in figure 3 between 760 and 765 nm, where the narrow width of the 0.05 nm filter resolves these features. As the filter width increases, these effects are smoothed since multiple absorption features are convolved by the bandwidth filters. All of the figures, except for figure 8, show that the largest signal-to-solar clutter absorption effect occurring near the D2 potassium doublet emission line at 766.49 nm, not only due to the larger D2 emission feature compared to the D1 line, but also because if the stronger atmospheric absorption that occurs between 760 and 765 nm compared with the spectral region near 769 nm where the D1 line is located (see figure 2). The transmission of the 5 nm filter (figure 8) includes both potassium emission lines and larger atmospheric radiance values which start at 769 nm where the suppressed radiance due to atmospheric oxygen end.

Table 1 shows the center wavelengths where the six filters have the highest signal-to-solar clutter ratio. The table 1 values for the 0.05, 0.5, 0.1, 1.0, 3.0, and 5.0 nm filters show the center wavelength where the maximum signal-to-solar clutter ratio occurs between 760 and 775 nm.

Figures 3-5 show that deviations from the center wavelengths, in table 1, may significantly alter the detected signal from small arms muzzle flash.

5.2 Selection of the Optimum Filter Bandpass

The selection of the best filter for small arms muzzle flash detection must take into account both the cost and the signal-to-solar clutter ratio. The 3 nm wide filter may meet both of these criteria, having the 2nd highest signal-to-solar clutter ratio of the six filters tested, and is low cost due to its wider width. Although figure 9 shows a general decrease in the signal-to-solar clutter ratio with increasing filter width, the trend is broken by the filters with widths of 0.5 and 3 nm. The signal-to-solar clutter ratio of the 0.5 nm filter increases due to the strong atmospheric absorption, shown in figure 2, that occurs in the middle of the D2 potassium emission feature at a wavelength slightly greater than 766 nm. The signal-to-solar clutter ratio of the 3 nm filter increases due to lower atmospheric absorption at wavelength less than 768 nm, shown in figure 2, and the skewed asymmetry of the D2 potassium line toward shorter wavelengths.

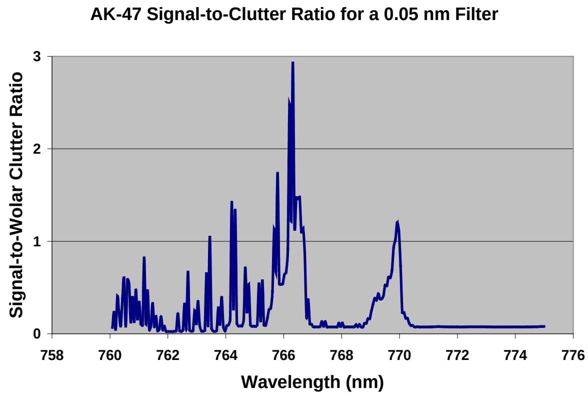

Figure 3. AK-47 muzzle Flash detected with a 0.05 nm FWHM filter.

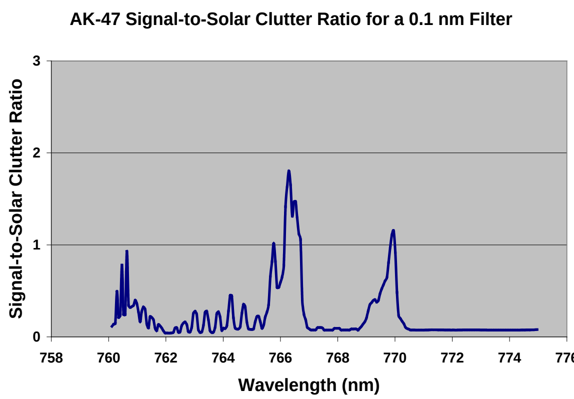

Figure 4. AK-47 muzzle Flash detected with a 0.1 nm FWHM filter.

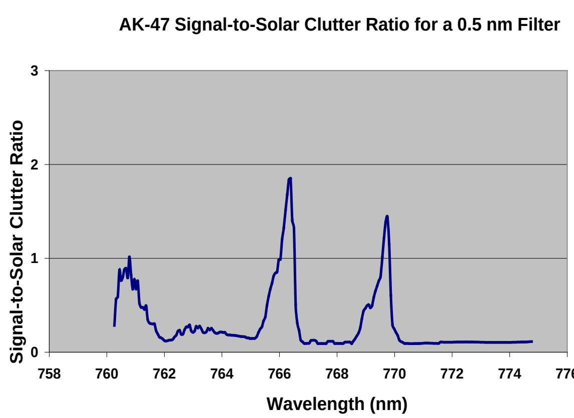

Figure 5. AK-47 muzzle Flash detected with a 0.5 nm FWHM filter.

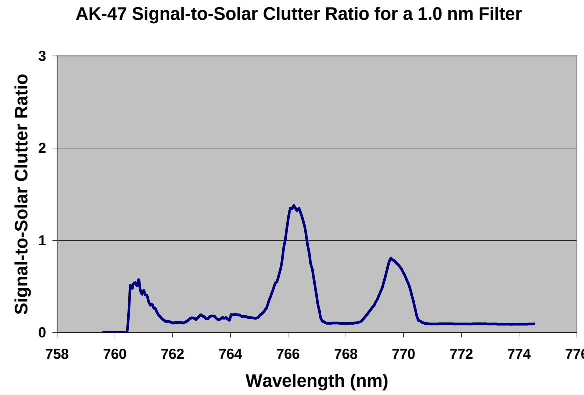

Figure 6. AK-47 muzzle Flash detected with a 1.0 nm FWHM filter.

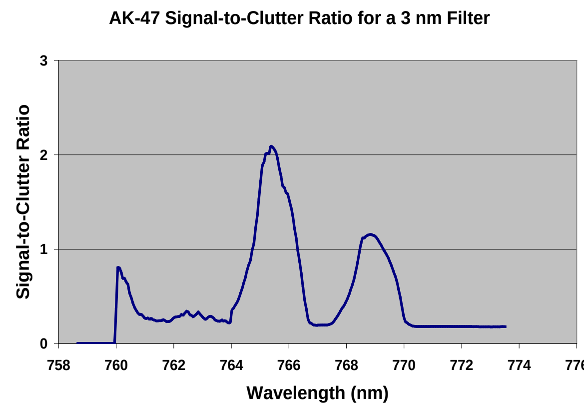

Figure 7. AK-47 muzzle Flash detected with a 3.0 nm FWHM filter.

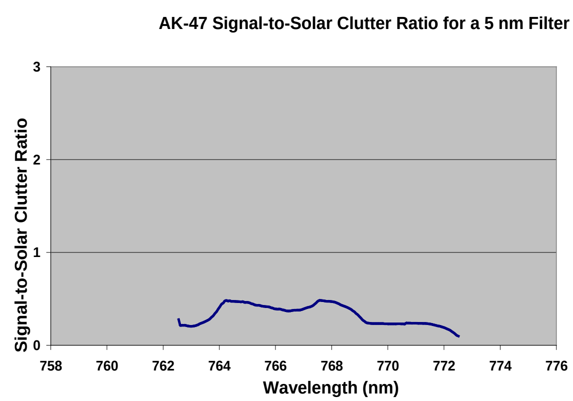

Figure 8. AK-47 muzzle Flash detected with a 5.0 nm FWHM filter.

Table 1. Center Filter Wavelength for Maximum AK-47 Muzzle Flash Detection

Filter Bandwidth (nm)	Center Wavelength (nm)	Signal-to-Solar Clutter Ratio
0.05	766.31	2.93
0.1	766.29	1.8
0.5	766.38	1.85
1.0	766.194	1.38
3.0	765.37	2.09
5.0	767.61	0.48

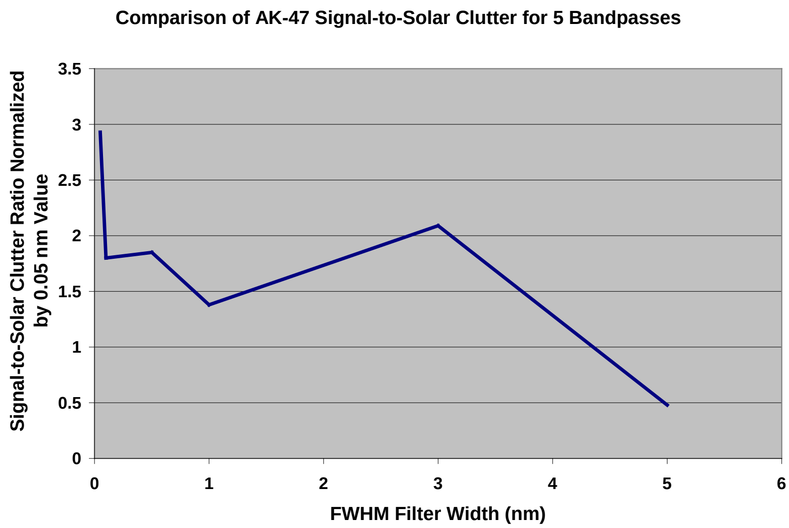

Figure 9. Comparison of AK-47 muzzle flash Signal-to-Atmosphere Ratio for six bandpasses

6.0 Conclusion

Evaluation of six filters, centered near the potassium doublet emission lines shows that daylight detection of an AK-47 muzzle flash may be possible. These findings counter the belief that only very narrow bandpass filters are capable of detecting small arms muzzle flashes. The 3 nm bandpass filter may be the best choice, due to its high signal-to-solar clutter ratio and relatively low cost. The wavelength sensitivity of these filters for muzzle flash detection point to further field experiments using silicon detectors, where various 3 nm filters are made with center bandwidths that would vary at 0.25 nm increments from 764 to 766 nm to understand at what center wavelength the maximum signal is achieved. Such additional tests would build upon this work to improve U.S. capabilities to detect future small arms threats.

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